Triggering, guiding and deviation of long air spark discharges with femtosecond laser filament

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In the perspective of the laser lightning rod, the ability of femtosecond filaments to trigger and to guide large scale discharges has been studied for several years. The present paper reports recent experimental results showing for the first time that filaments are able not only to trigger and guide but also to divert an electric discharge from its normal path. Laser filaments are also able to divert the spark without contact between laser and electrodes at large distance from the laser. A comparison between negative and positive discharge polarities also reveals important discrepancies in the guiding mechanism.

I. INTRODUCTION

If lightning is one of the most fascinating phenomena occurring in the atmosphere, it is also one of the most dangerous. This spark discharge of several kilometers can cause severe damages to ground infrastructures. During history, several techniques have been developed for lightning protection, such as Benjamin Franklin's famous lightning rod or the rocket triggering device [1]. The laser lightning rod would be a valuable alternative to lightning rockets. This concept relies on the generation by powerful lasers of a long plasma column acting like an extension of the classical rod toward thunder clouds and would be able to significantly empty electrically charged clouds preventing lightning stroke to hit sensitive building or facilities.

Imagined in the early 60's the concept of laser-triggered discharges was first investigated with high energy CO_2 and YAG lasers [2]. Despite the first real scale demonstration of triggering in 1996 [3], this path was progressively abandoned because of the discontinuous profile of the plasma generated with such long pulses through avalanche breakdown [4]. Following the development of femtosecond CPA (chirped pulse amplification) laser systems, the study of ultrashort filaments in air [5] and their ability to generate a thin uniform plasma channel over very long distances opened new perspectives in the field [6- 10].

Laser filamentation is a nonlinear propagation regime affecting femtosecond laser beams provided their peak power exceeds a critical value (5 GW at 800 nm in air). A dynamical competition between Kerr effect which tends to self focus the beam, diffraction and multiphoton ionization which defocus the beam leads to the formation of self guided light pulses called filaments maintaining a high peak intensity over long distances [11-13]. These self guided pulses leave in their wake a uniform weakly ionized plasma column [14-15]. Laboratory scale experiments of large discharges guiding by filamentation in a plane rod geometry have demonstrated the ability of filaments to decrease the breakdown threshold by 30% [7-8] and to guide the spark over 2 to 3 meters for positive upward leader [9-11] and for negative upward leader [18].

In this manuscript we study the guiding efficiency of filaments with a positive and negative voltage in plane/rod electrode rod geometry. We also report the first demonstration of the possibility to deviate a long spark discharge from its natural point of attachment. Finally the guiding of discharge without contact between laser and electrodes is investigated.

II. INFLUENCE OF THE VOLTAGE POLARITY

A. Experimental setup

Experiments were performed at the DGATA center in Toulouse in the high voltage facility FOUDRE. The first experimental setup is presented in Figure 1. A large planar electrode connected to a high voltage Marx generator was placed 2.5 m above a spherical one (15 cm of diameter) connected to the ground. The high voltage generator could deliver up to 2 MV in both polarities. The voltage applied consisted in a standard voltage waveform modeling a fast lightning process. To produce the plasma filament, the laser ENSTAmobile built by Amplitude Technologies was used. This laser is a mobile Ti:Sa CPA laser chain delivering pulses of up to 350 mJ energy with a duration of 50 fs (7 TW) at a repetition rate of 10 Hz. To postpone the onset of filamentation and transport the beam without damaging the optics, a linear chirp of about 15000 fs^2 was impressed to the pulse. The laser beam of 40 mm diameter was weakly focused in order to create the plasma filaments tangentially to one side of the sphere electrode. The plasma column was composed of a bundle of 80 filaments starting at a distance of 7 m after the lens and continuing over a distance of 4 m. In the gap separating the two electrodes, the multiple filaments formed a quasi homogeneous circular plasma column several mm in diameter. The current I_1 circulating through the electrode was measured with a Rogowski coil, while the voltage V on the planar electrode was measured through a resistive probe.

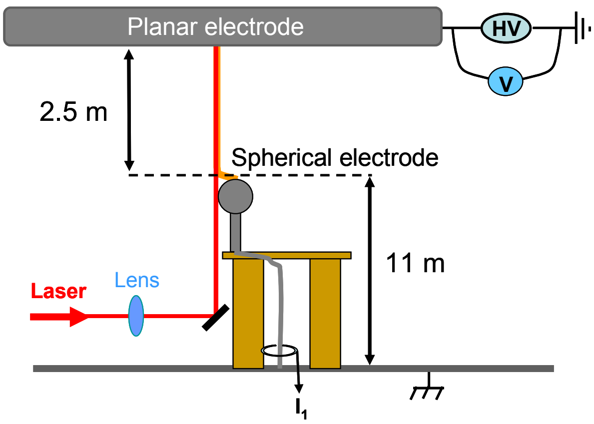

FIG. 1. Experimental setup.

B. Results and discussion

Figure 2(a) shows a still image of an unguided discharge obtained in the absence of laser with a voltage V = -1.3 MV applied to the plane electrode. The corresponding temporal evolution of the voltage on the charged electrode and the current circulating in the spherical electrode is presented in Figure 2(b). Figures 2(c) and 2(d) show the same measurement when a plasma filament is formed between the electrodes at time t = 0 s, during the voltage rising front. In this case the discharge path is perfectly straight and follows the filament axis, showing that the guiding is achieved over the full length of the discharge.

It has been shown that the plasma column formed by laser filaments can lower the breakdown field by 10 to 30 % [8-9]. Here we investigate the evolution of this effect as a function of the delay τ_L between the beginning of the voltage front and the laser filament formation. The average peak electric field between the electrodes is defined as the maximum applied voltage divided by the separation gap. The value of this average field is plotted in Figure 3 as a function of τ_L for a positive (Figure 3a) and a negative applied voltage (Figure 3b). The natural breakdown field in absence of laser filament is measured for both polarities and indicated in the graphs by the dashed orange line. It is equal to 8 kV/cm for a positive voltage polarity and to 5.2 kV/cm for negative voltage polarity, which are close to the stability field amplitudes for streamer reported by Gallimberti *et al.* [19].

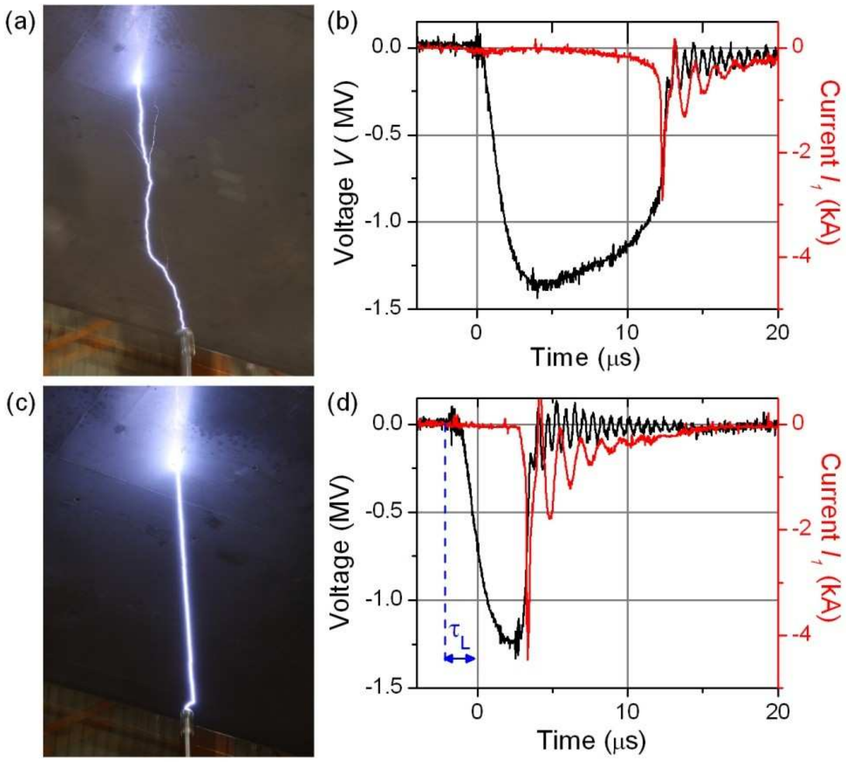

FIG. 2. Integrated picture of the discharge and measurements of the voltage and current in the case of an unguided discharge (a,b) and laser guided discharge (c,d).

As shown by the blue stars in Figure 3, when the discharge is guided over the full length by the filament, the breakdown field can be decreased to 3.6 kV/cm for positive voltage and to 4.3 kV/cm for negative voltage. This corresponds to a decrease of the breakdown field of 55 % and 7 % respectively. The smaller decrease with the negative voltage might be due to the fact that negative leader propagate slowly compared to positive leader [4] (see also discussion later). Partially guided discharges are also presented in Figure 3 as green dots. Such discharges were only observed with negative voltage polarity. Most of them were obtained when the laser pulse arrived after the voltage was applied, while fully guided discharges occurred when $\tau_L \sim 0$. Concerning the establishment of the guided discharge, with negative applied voltage the mean delay between the laser and the guided discharged was 4.2 µs with a high fluctuation (around 1.36 µs). By contrast, fully guided discharges obtained with a positive voltage occurred always with a short delay between the onset of the voltage and the laser arrival (0.97 µs in average). In this case, the delay between the laser and the discharge was very reproducible with a standard deviation of 0.54 µs, as shown in Figure 4.

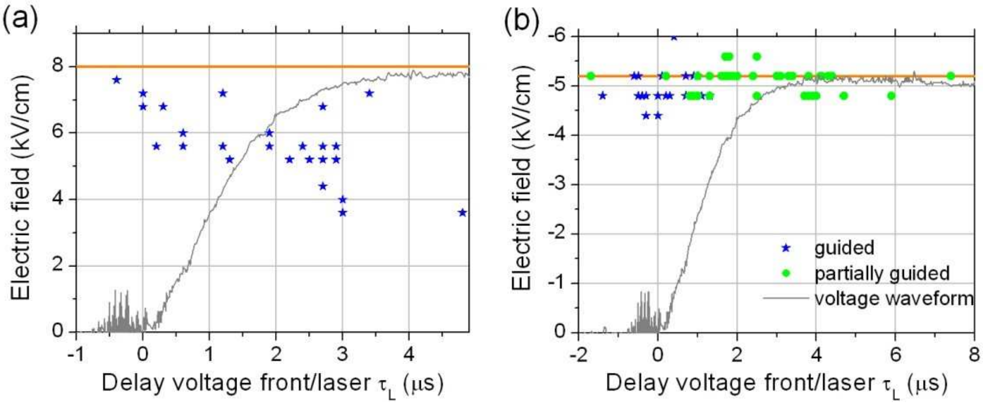

FIG. 3. Average breakdown field with the laser as a function of the delay τ_L between the voltage front and the laser filament for a positive (a) and a negative applied voltage (b). Breakdown voltage in absence of laser is shown as a dashed orange line and the grey continuous line shows the corresponding voltage waveform.

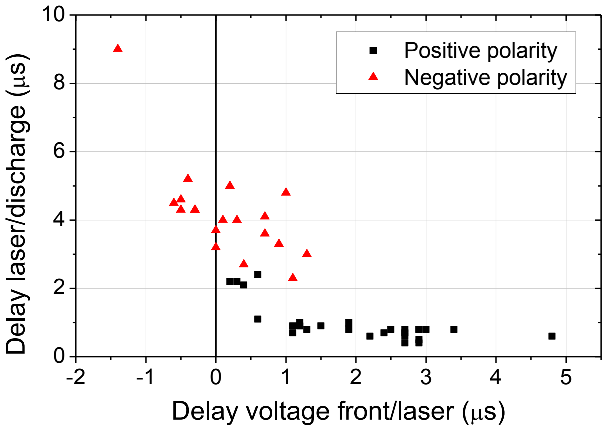

FIG. 4. Delay between the laser pulse and the triggered discharge as a function of the delay between the voltage front and the laser for a negative (red triangles) and a positive (black squares) applied voltage.

Because of the size and shape of the HV electrodes, the electric field in the gap is strongly asymmetric and the breakdown is initiated by ascending streamers/leaders from the sphere electrode. A discharge obtained with a positive polarity on the HV electrode corresponds to the propagation of an ascending negative leader, and *vice versa*. As a consequence of the differences between negative and positive leader characteristics and propagation speed [4-19], results obtained with positive and negative polarities are quite different. Estimation of the negative discharge velocity based on the delay between the laser and the spark gives $V_- = 2.5\text{x}10^6$ m/s, in good agreement with previously reported values for laser guided negative leader velocities [18]. For comparison a similar estimation for the positive discharge gives $V_+ = 6\text{x}10^5$ m/s.

III. DEVIATION OF A DISCHARGE BY LASER FILAMENT

A. Experimental setup

A second experiment was performed to demonstrate the possibility to deviate a discharge from its natural impact point. The setup was the same as previously but a second electrode connected to the ground (named A in Figure 5) was placed besides the spherical electrode (named B) to represent a critical site. Electrode A was a sharp tip placed 30 cm closer to the planar electrode than electrode B. Tip and sphere electrodes represent respectively a natural geometrical reinforcement of a structure to protect and a sacrificial lightning diverter. Consequently, without the application of the laser, the natural discharge always occurred on electrode A.

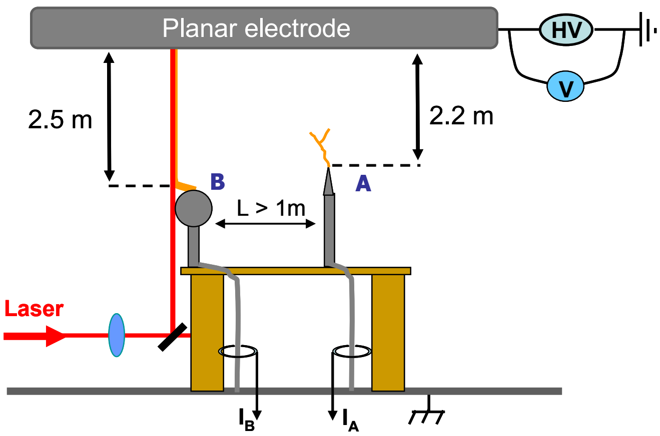

FIG. 5. Setup principle for deviation tests.

B. Results and discussion

In this configuration, when the laser synchronization was adjusted according to the values determined previously, the discharge was always triggered and guided on the diverted path starting with electrode B (see Figure 6). The process is efficient in both voltage polarities and its reproducibility has been checked over 30 shots.

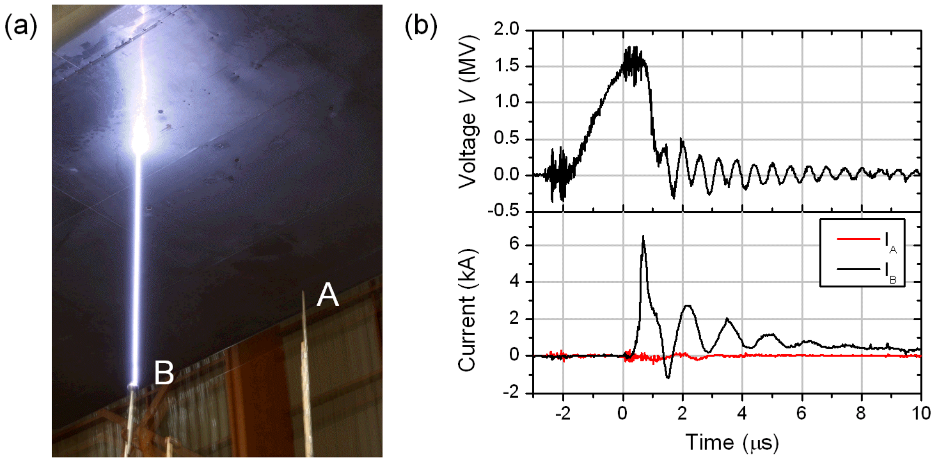

FIG. 6. Image of a deviated discharge with a positive applied voltage polarity. Corresponding voltage and current signals are presented on the right. Time t = 0 corresponds to the arrival of laser pulse.

A striking feature is the fact that guided and diverted discharges were obtained even if a spontaneous discharge starting from the tip electrode had already been initiated, as shown in Figure 7(a). In Figure 7(b), it is clearly seen that a slowly rising current corresponding to the natural discharge is first detected on the tip, but it drops quickly to zero with the abrupt rise of the current measured along the guided discharge.

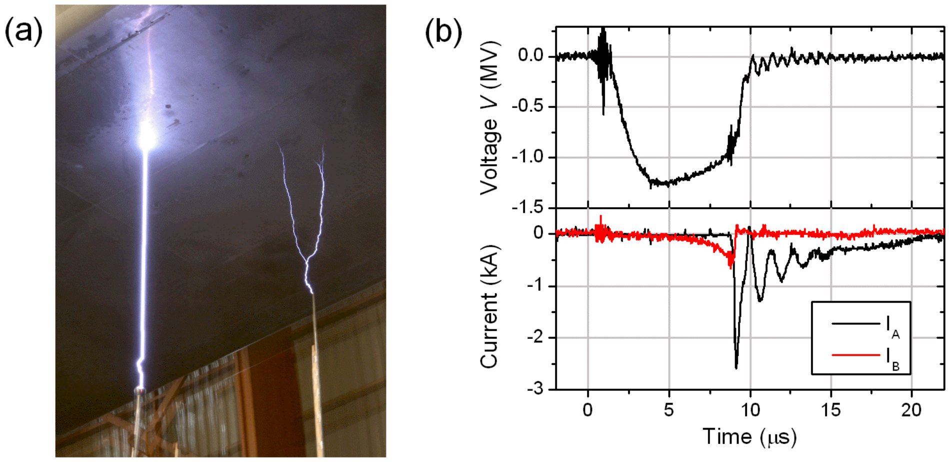

FIG. 7. Image of a deviated discharge with negative applied voltage polarity where streamers start to develop on the tip. Corresponding voltage and current signals are presented on the right. Time t = 0 corresponds to the arrival of laser pulse.

IV. LASER GUIDED DISCHARGE AT LONG DISTANCE

A second test campaign has been also performed at DGATA center during October 2010. The purpose was to demonstrate that guiding of discharges was possible at long distances from the laser and with higher discharge current. Laser triggering of high power discharges with long duration has been reported in ref. [20] with centimeter scale gaps at a distance of 20 m from the laser. In this experiment we intended to guide discharge currents close to typical values in negative lightning stroke with relatively large gap lengths at larger distances from the laser. The experimental set-up is shown in Figure 8. To achieve a large distance between the laser source and the discharge area, we have used a mobile HV generator producing voltage waveforms having a fast rise (4 μs) and a long decrease (7 ms) with a maximum voltage of 450 kV corresponding to a discharge current of 37 kA. The ground electrode consisted in a short metallic cylinder, with an inner diameter of 50 mm, through which the laser was propagating. The HV electrode was a metallic sphere, set typically 60 cm from the ground electrode. The laser beam was expanded and focused by a telescope to produce a continuous ionized channel between the electrodes. The voltage on the second electrode was measured with a resistive probe, while the discharge current flowing from the grounded electrode was monitored through a Rogowski coil. Triggered and guided discharges were obtained reliably at a distance of 50 m from the laser, the maximum possible distance inside the building containing both the laser and the HV generator.

Examples of guided and unguided discharges and the corresponding current and voltage signals are shown in Figure 9. Guided discharges with current exceeding 30 kA were obtained with a good reliability. At the same applied voltage level an increase of the discharge current of 6 % was observed when the discharge was guided by the laser.

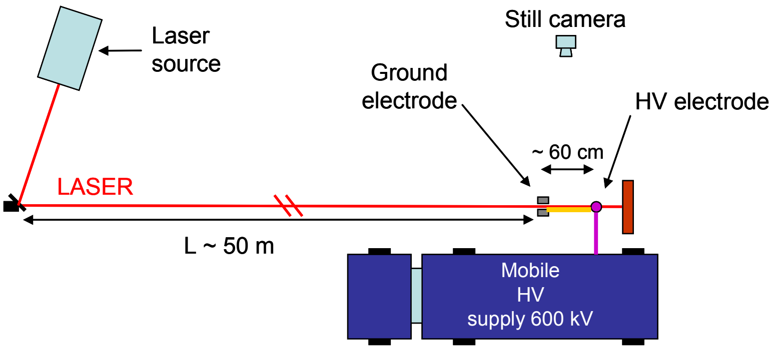

FIG. 8. Setup principles for long distance laser guiding of discharges.

In this configuration the field induced between the electrodes is almost symmetric due to electrodes geometry. For this reason discharge inception happens simultaneously on both electrodes resulting on a poor dependence of the applied voltage polarity. We measured a breakdown field of 7 kV/cm for negative polarity and 6.7 kV/cm for positive polarity. As shown in Figure 9(b) natural discharges often present a double arc structure. In the presence of laser filament decreases of the breakdown voltage of 12% and 35% were obtained with negative and positive polarity respectively. The only noticeable difference between the voltage polarities concerns the optimal delay between the laser and the voltage front.

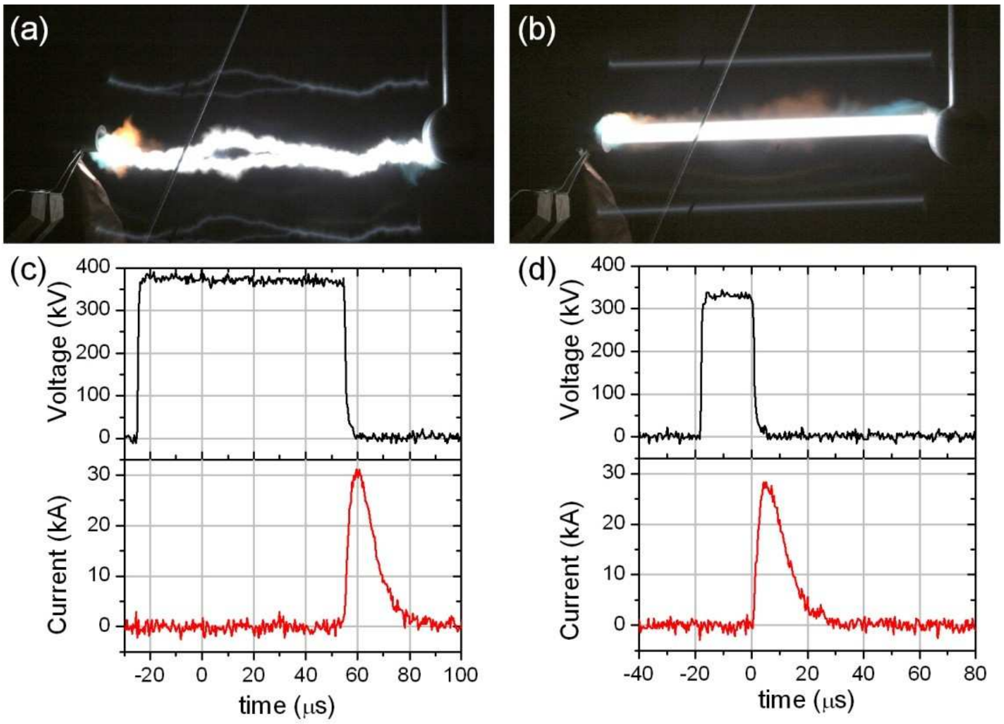

FIG. 9. Example of an unguided (a) and guided discharge (b) obtained with the two electrodes aligned on the laser axis and with a gap of 60 cm. The discharge current reaches 30 kA for an applied voltage of +360 kV. In the guided case the laser is sent at time $t = 0$ s.

V. LASER GUIDED DISCHARGE WITHOUT CONTACT BETWEEN LASER AND ELECTRODES

The purpose was to assess the sensitivity of triggering and guiding to alignment conditions, especially unfavorable electric field configurations where the laser path was not in contact with the HV electrode and the laser was not parallel to the electric field. In a previous experimental study Fuji *et al.* [21] reported guiding of discharge without contact between the first electrode and the filament. They also observed the appearance of a slow discharge mode when the distance electrode/filament exceeds 5 cm.

A. Experimental setup

The set-up was the same as in Figure 8 except that a misalignment of the electrodes with respect to the laser path was deliberately introduced, as shown in Figure 10.

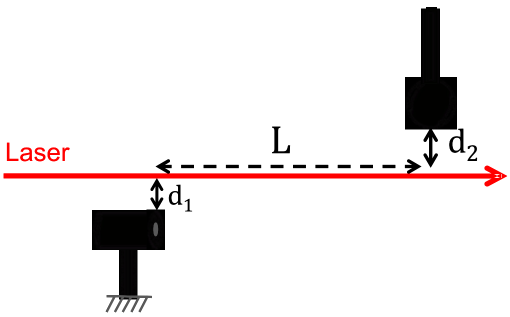

FIG. 10. Experimental setup. L is the gap length, d_1 the distance from the first electrode and d_2 from the second electrode.

B. Results

A result of guided and unguided discharge for a displacement of the second electrode d_2 = 20 cm is shown in Figure 11. In the absence of filament the discharge follows a quasi direct trajectory given by the field lines inside the gap. When the filament is formed in the gap it is able to deviate the discharge path increasing the discharge length by ~30%. Similar results were obtained with a negative polarity.

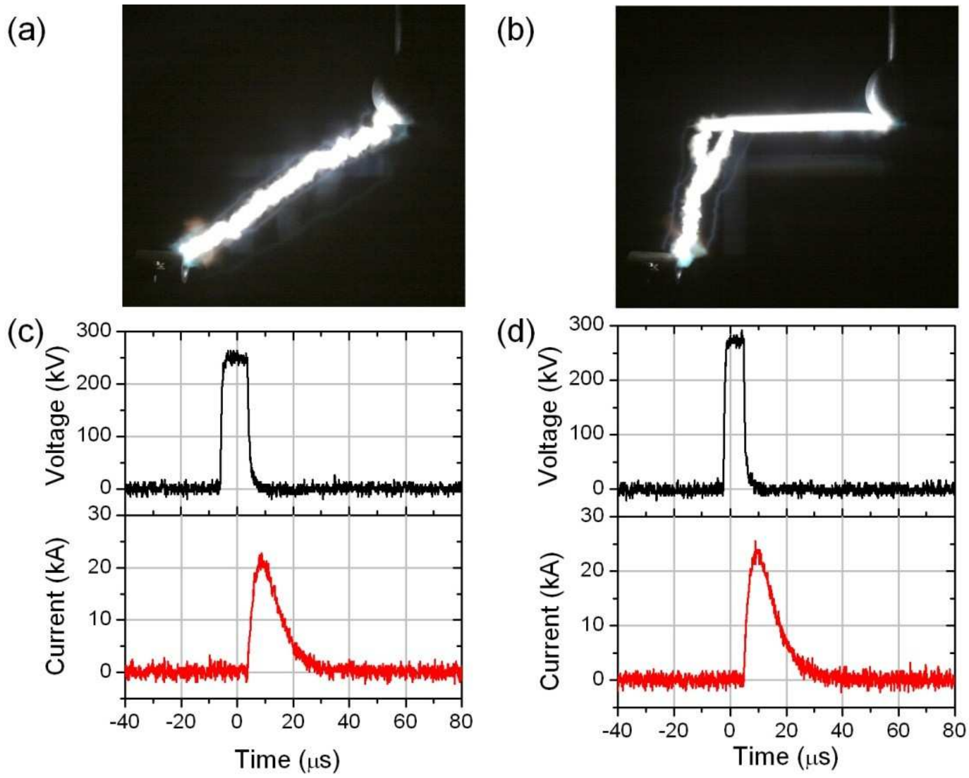

FIG. 11. Unguided and guided discharge obtained with the first electrode 20 cm away from the filament. L = 30 cm, d_1 = 20 cm and d_2 = 0 cm.

The maximum separation allowing laser guiding was 20 cm for d_1 and 13 cm for d_2 (see illustration on Figure 12(a)). When both electrodes were displaced the guiding was maintained up to d_1 = 5 cm, d_2 = 5 cm (Figure 12(b)).

Again, we observed that this guiding was very robust as long as the delay between laser and voltage pulse was maintained at an optimal value.

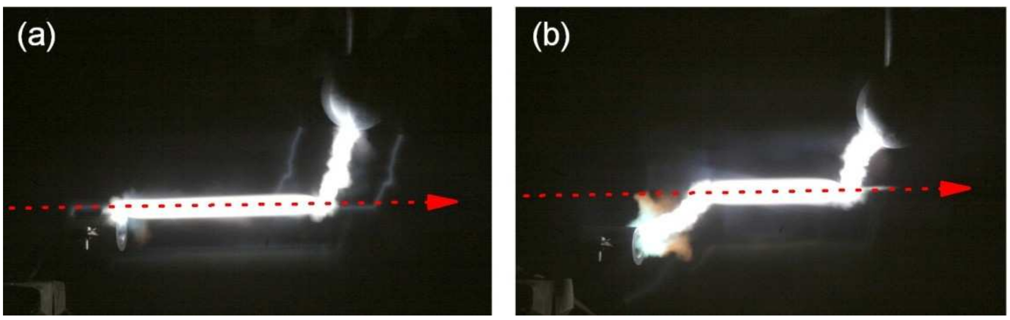

FIG. 12. Images (side views) of guided discharge obtained with the second electrode 20 cm away from the filament (a) and with $d_1 = d_2$ = 5 cm. The gap length was L = 30 cm.

For all results presented in Figures 11 and 12 the plasma filament was placed in the plane defined by the two electrodes which contains the lines of maximum electric field. We also tested a scheme in which the filament was laterally displaced with respect to electrode gap. In this case the discharge deviation by the laser was not as systematic as in the previous case but several shots were positive.

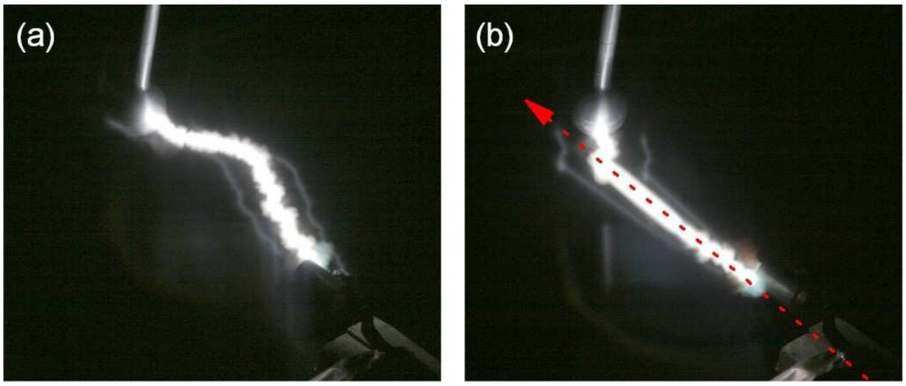

FIG. 13. Images (top views) of free (a) and guided (b) discharges obtained with laser propagating laterally 5 cm away from the electrodes gap. The gap length was $L = 30$ cm.

VI. DISCUSSION

A. Guiding mechanisms

In order to discuss the results, it is useful to recall the mechanism by which the laser filament initiates an electric discharge. The femtosecond pulse creates a plasma column of quasi constant initial electron density extending between both electrodes. This plasma column disappears by two processes. The electrons can recombine directly to the parent ions or they can be captured by oxygen molecules. Recombination on parent ions occurs within 1 ns, whereas the recombination by attachment follows an exponential law of 150 ns decay time [22-23]. After the attachment process, these negative oxygen ions have a long lifetime (up to tens of millisecond), limited by diffusion of O_2^- molecule-ions out of the filament region and therefore they keep for a long time memory of the filament geometry [24]. The static external field accelerates free electrons which release their kinetic energy by Joule heating leading to the formation of a hot air column. The heated air column then expands radially leading to the delayed appearance of a depressurized channel at the center of the filament path. The resulting low density column offers a privileged path for discharge [25-27]. In parallel, electrons loosely bound on neutral oxygen molecules can be easily released by current heating, leading to a decrease of the critical temperature for leader development [28]. This explains why fully guided discharges can develop even if the laser pulse is applied well before the voltage pulse, as seen in Figure 3.

B. Influence of the voltage polarity

We now discuss the effect of voltage polarity observed in part II, following models described in the literature for long air gap discharges (> 1 m) [4,19]. Due to the electrodes geometry the field induced between the electrodes is strongly non uniform and its amplitude is much larger near the sphere than near the planar electrode as shown in Figure 5. For this reason the discharge is expected to start always from the sphere electrode, as indeed observed in the experiments.

For a negative polarity applied to the planar electrode, a positive upward leader is developing from the top of the spherical electrode. This leader develops as follows. When the high voltage waveform is applied, the free electrons present in the air near the spherical electrode are accelerated and produce other free electrons by avalanche effect. These electrons are moving toward the direction of an increase of the field and regroup near the electrode. A corona discharge thus appears with the development of a streamer bundle. Within the risetime of the voltage pulse, these positive streamers can attain a typical length of 1 m in 1 µs with an appropriate local external field. These streamers regroup at the stem of the corona in a hot plasma (T ~ 1500 K) column which progresses toward the high voltage source: the leader. The positive leader propagation is sustained by the corona discharge at its tip which provides the current necessary to heat the leader. When the leader propagates, it increases locally the electric field at its extremity leading to a further enhancement of the corona discharge. Consequently, the leader development process is a coupled phenomenon between a hot plasma column (the leader) and the local discharge which sustains it (the tip corona). When the positively charged leader reaches the negative high voltage electrode, the return stroke induces the spark discharge.

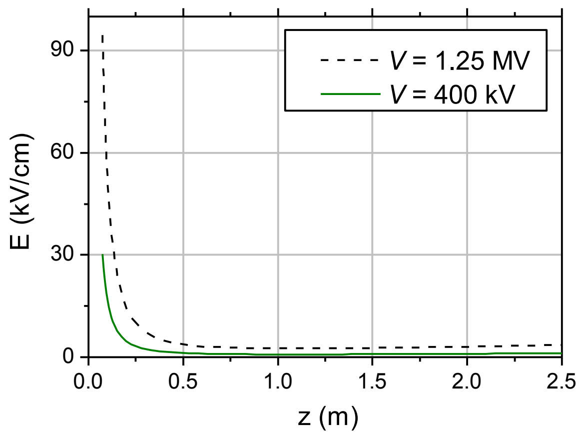

FIG. 14. Calculated on axis electric field induced between the sphere (z = 0) and the plane electrode (z = 2.5 m) presented in Figure 1 for an applied voltage of 0.4 and 1.25 MV corresponding respectively to the streamer inception voltage and the average breakdown voltage in presence of the laser filament.

As noted above, the main role of the laser filament is to offer a preferential path for the streamers and the leader. In the case of positive upward leader the transition from streamer inception to leader is very fast, especially when the voltage rise time is as short as in our case. For this reason it is difficult for the filament to guide the discharge once the streamers have started to develop. We further elaborate on this point. Electrostatic calculations show that the electric field on the top of the sphere is about three times higher than the field at the point of contact with filaments, on the edge of the spherical electrode. This means that the field at the top of the electrode will reach the value of 30 kV/cm necessary for streamer inception at the edge of the rising voltage front when the rising voltage reaches the value of 400 kV (see Figure 14). This value is in good agreement with measurements from the literature [7, 29] and corresponds to an averaged field of 1.6 kV/cm. Therefore in order to prevent the development of spontaneous streamers nascent at the top of the spherical electrode, it is necessary to offer a preferential path though filamentation before this critical field is reached. We note that all fully guided discharges obtained with negative applied polarity appear indeed when the laser arrives before the voltage has reached this value (see Figure 3b). By contrast, all partially guided discharges appear when the voltage at the time of laser arrival is higher than the inception voltage. Furthermore the unguided part of the discharges always starts at the top of the spherical electrode.

At positive polarity on the planar electrode, electrons appear close to the spherical electrode at the same inception voltage but streamers development is much slower, since electrons move toward a decrease of the field, which inhibits their multiplication. For this reason, the required average field for the development of a leader is two time larger [4] As a consequence, there is a larger time interval during which a hydrodynamic expansion of the filament heated air column can develop in the absence of perturbing streamers, defining a better preferential path for the discharge. In this case the decrease of breakdown voltage and the delay between filament arrival and the onset of a guided discharge is mainly ruled by the hydrodynamics of the hot air column. This explains the more pronounced decrease of external voltage required for discharge guiding and the short and reproducible time interval between arrival of the filament and the initiation of the discharge seen in the measurements. In some cases long negative discharges can develop by discrete steps with the formation of space charge leaders inside the gap [19]. The diagnostics used in our measurement did not allow us to show evidence of these phenomena, which generally appears in larger gaps [16, 29].

C. Implications for a laser lightning rod

The obtained results are very encouraging in several aspects for the triggering and the guiding of lightning towards a safe sacrificial site. First, the presence of a filament obviously decreases the voltage required to obtain a discharge. This effect can occur at long distances from the laser. We remind that ionization induced by filamentation has been measured recently up to 1 km distance from the laser [17]. The decrease of dielectric breakdown can reach a factor two for positive discharges, which would correspond to situations where the bottom of a cloud is positively charged. Furthermore, the initiation of the triggering of an electric discharge is flexible in terms of alignment. It is not necessary to have the filament propagating perpendicular to the electric field lines. For negative discharges, the diversion of the discharge from a preferential natural path can occur even if the natural discharge has already started. The preferential path defined by the filament track is somewhat analogous to the conditions of a dart leader in lightning, when a plasma channel from the first leader is present One should also note that the voltage waveforms used in our measurements present a much shorter risetime than the one observed in real lightning storm [30]. The sensitivity of the guiding effect on the time delay between laser and voltage front should be much smaller in real condition where the on ground potential grows on a millisecond timescale.

VII. CONCLUSION

We have demonstrated the ability of the filament to deviate long air gap spark discharge from their natural point of attachment. When the delay between the laser and the voltage pulse are cleverly optimized the deviation is 100% efficient for both voltage polarities. We also observed a very important reduction in the threshold voltage (especially for a positive polarity) with laser filament. Filament induced triggering and guiding has been observed at a distance of 50 m from the laser, a distance limited by the available space. We have also observed filament guided discharges even when a natural discharge had already started from a rival tip electrode. All these results are encouraging for the realization of a laser lightning rod.

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